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Use of Forest Site Index for Evaluating Terrestrial Resources at Risk from Acidic Deposition

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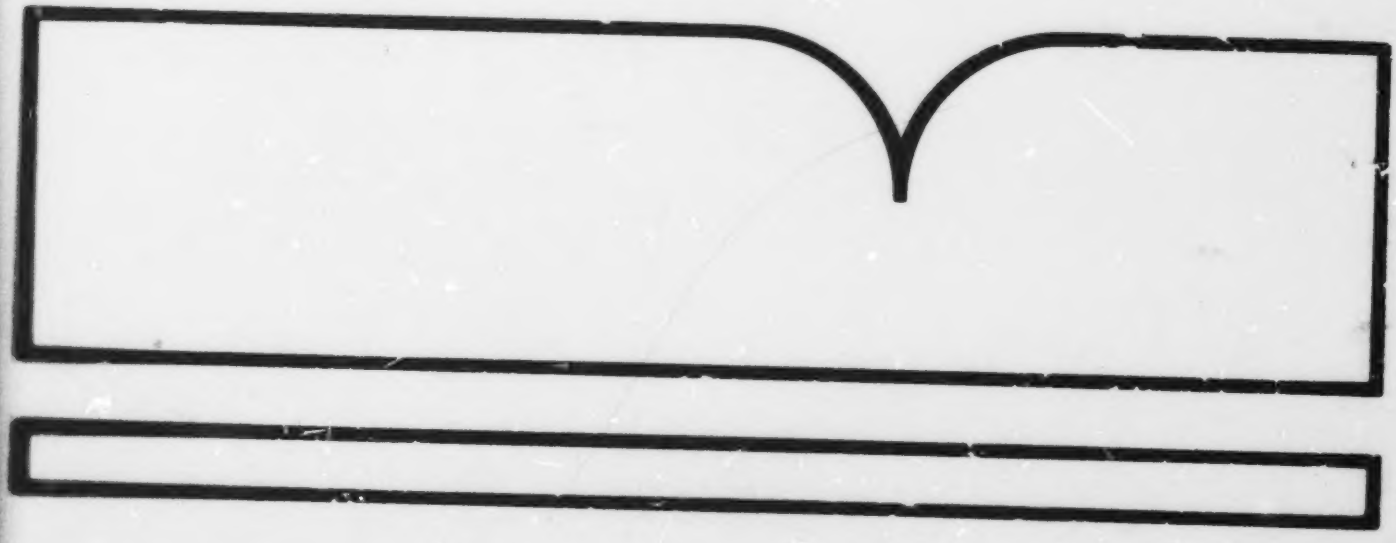

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16. ABSTRACT

The principal goal of this chapter is a discussion of the applicability of forest growth measurement to the detection of acidic deposition impacts on forest growth. The chapter has grown out of studies undertaken for EPA on the quantification of linked land and water system responses in watersheds [3] following addition of acidic deposition, with an emphasis on integrative measures of terrestrial and aquatic effects in the same watershed [4].

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Edited by Rick A. Linthurst

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CHAPTER 8

Use of Forest Site Index for Evaluating Terrestrial Resources at Risk from Acidic Deposition

Orie L. Loucks

A major body of literature has dealt with effects on height and diameter growth of tree species exposed to moderate concentrations of gaseous air pollutants. Many of these results have been summarized [1,2], but there still is an urgent need to consider the potential for effects on forest growth from acidic deposition. In particular, the relatively sophisticated measurement methods and models available from the field of forest mensuration should be considered for use in evaluating effects on forest growth from the alteration of forest soil chemistry following input of acidic deposition. Thus, the principal goal of this chapter is a discussion of the applicability of forest growth measurement to the detection of acidic deposition impacts on forest growth. The chapter has grown out of studies undertaken for EPA on the quantification of linked land and water system responses in watersheds [3] following addition of acidic deposition, with an emphasis on integrative measures of terrestrial and aquatic effects in the same watershed [4].

Locally focused studies have reported effects of sulfur dioxide (SO_2) gas on forests in Washington [5], Ontario [6], Virginia [7], Wisconsin [8] and Alberta [9]. These studies have shown either greatly reduced height and diameter growth, or actual mortality of the trees over a number of years, in each case attributed to local sources of SO_2 acting alone or in combination with other pollutants. Studies by Miller [1], in the San Bernardino Mountains of California, by Skelly [10], in Virginia, and by McLaughlin et al. [11], in Tennessee, have shown the more general regional response of woody species to moderate exposures of oxidants, primarily ozone (O_3). In both groups of studies, reductions have been shown in the annual rate of either height or diameter growth, with effects on height being expressed more strongly on younger stems.

Given this widespread evidence of the sensitivity of tree species to air pollutants, both locally and regionally, numerous researchers have sought to document the potential for a similar response in forest growth to the annual deposition of acidic substances in rainfall. The results to date, however, have been inconclusive

[2,12,13]. These findings may be due to imprecision in the methodologies being used to document height or diameter growth changes. They may be the result of growth having been altered already by other regionally elevated air pollutants, or the effects of acidic inputs may be neutral or even positive due to the sulfur and nitrogen nutrient content. A further objective of this chapter, therefore, is to review the background on chemical alteration of the forest environment (deposition of acidic substances and soil chemical responses), and to examine the application of forest mensurational methods in the context of a specific case study of soil nutrient stocks and site index in northern Wisconsin.

FOREST MEASUREMENT OPTIONS

A long record of forestry literature documents the diverse influences controlling height and diameter growth of trees [14–17]. This research has been cast largely in a context that recognizes the product of interest from forests (aside from recreational areas) is wood volume or its equivalent in cellulose mass. Thus, forest productivity of local study sites, watersheds or large industrial forest tracts are expressed routinely in cubic feet (or cubic meters) of annual growth per unit area (e.g., m^3-ha^{-1}-y^{-1}). This annual volume increment is controlled, in part, by the annual increase in diameter (i.e., cross-sectional or basal area), but the volume of a tree can be viewed most simply as a cone (Figure 1), and is, therefore, strongly controlled by height as well as cross-sectional area or diameter. Since, as we shall see, the diameter of the tree is more sensitive to the idiosyncracies of local competition from nearby stems, the total height of the cone (particularly for the population of cones that represents a fully stocked stand) is viewed as a more reliable measure of overall long-term forest productivity [12,13].

Of these two, the more readily measured property of trees is stem diameter. Indeed, because of the difference in density between spring wood and summer wood, most species leave a well defined record of the annual increase in diameter that can be reconstructed years later through tree-ring analysis. This record has been used [18] and is currently proposed for more extensive use in evaluating air pollutant effects on forest growth, including acidic deposition.

Problems emerge, however, because of the profound sensitivity of diameter growth to the aging of individual trees, the effects of competition from nearby stems (a density effect), annual variations in climate (particularly precipitation and temperature) and unusual local influences from shallow soils, which may not affect a young developing forest but have large effects on slowing growth in a fully developed stand. In addition, variations in responses among species add complexity to understanding the patterns of diameter responses.

Height growth of trees is linked in a general way to overall growth (including diameter growth), but the variance in mean height growth can be reduced greatly by explicit choice of "dominant" and "codominant" stems for measurement and analysis [14]. By definition, these trees have not experienced significant shading or serious competition from adjacent stems throughout their life span, thereby minimizing the density effects reflected in diameter measurements. Although a

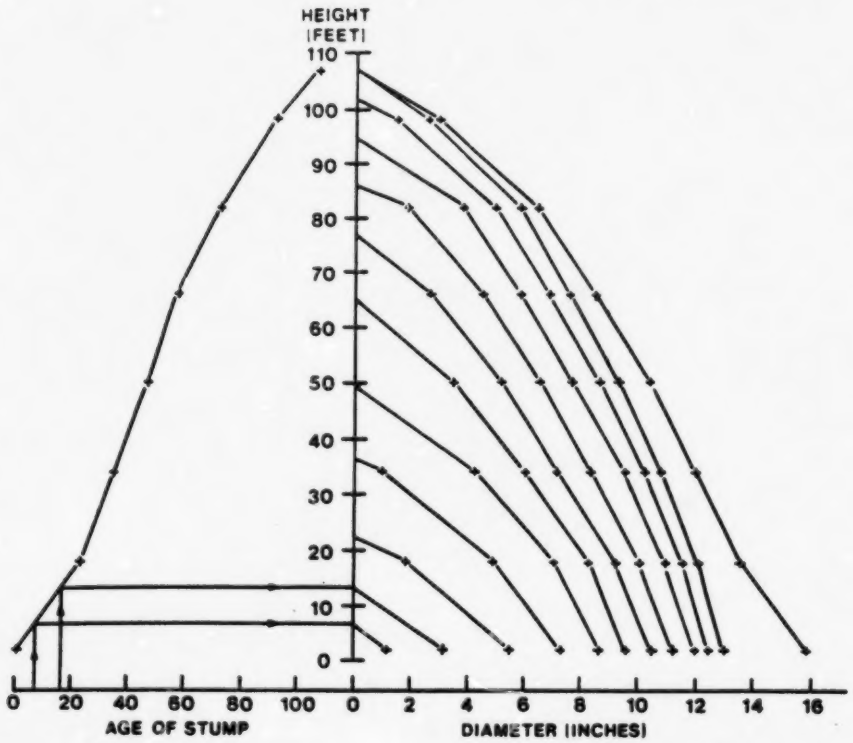

Figure 1. Tree-form analysis [14] showing the relationship between height and diameter increments in a tree as obtained by stem analysis methods. The outermost line represents outside-bark measurements; the series of concentric inner cones represent groups of annual rings in the wood which narrow rapidly at the base in later years.

general relationship exists between height growth and fluctuations in climate, much of the height increment occurs as a burst of growth in the spring derived in part from the previous year's carbohydrate accumulation and partly from the current year's growing conditions.

Most importantly, the gradual development of the height of an entire stand is a property of the whole forest, as well as of the individual dominant stems. Therefore, height represents a condition of the forest as it responds to its environment, including any alterations of that environment by chemical pollutants. For example, the effect of oxidants on both height and diameter of ponderosa pine is shown in Figure 2 [1]. Thus, to evaluate the alteration of forest productivity over some period of time, as might be the case with acidic deposition, one should use a stand property that averages over a multiyear growing period and can capture the average height response of the population of stems controlling total volume. Because a stand can be defined as fully stocked at either high or low density

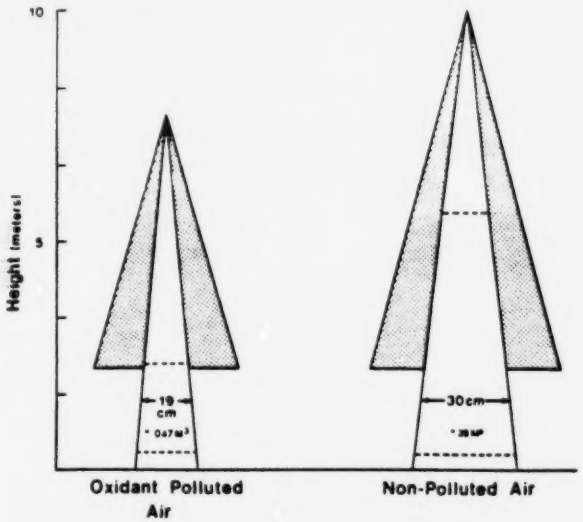

Figure 2. Calculated average growth of 30-year-old, 15-cm ponderosa pines at San Bernardino National Forest, California, in polluted and nonpolluted air based on radial growth samples from 1941–1971 and 1910–1940 [1]. The asterisk indicates wood volume in log with 15-cm top (minimum merchantable diameter).

(i.e., low or high average diameter), the plastic measure represented by diameter growth is difficult to use as a long-term characterizing property of the stand.

Consideration of model characteristics needed for projecting future responses also indicates the desirability of working with a measurement property with a background of predictive uses. The forestry literature has developed such a measure, known primarily as "forest site index" (FSI) [14,15]. This measure expresses stand height growth for a given combination of soil and species over a standard time interval such that in the absence of human alteration consistent values are obtained from one forest rotation to the next. Site index is most commonly expressed as the average height of dominant and codominant trees at an age base of 25–50 y (in the East) or 100 y (in the West). Measurements taken on trees younger or much older than this age base can be converted to the standard base through the use of established curves or tables, available for most species [14,16,17].

FSI has been used for almost a century in Europe and North America as a standard measure of both current and potential forest productivity. The wide agreement on its use derives, in part, from the facility with which the height of trees, multiplied through full stocking or standard basal area, converts to cubic volumes or dollar value of wood products. Decades of research on growth rates and harvestable yields in relation to height, stem density and basal area (average diameter) are summarized in standard yield tables [16].

Quantifying pollutant impacts on a resource such as a forest stand requires one to distinguish among properties of the system that have varying degrees of sensitivity to pollutant exposures. The observer must differentiate between two general groups of measures: "indicators," individual high-resolution response measures of components within a complex system (i.e., a chemical nutrient stock), and "integrators," measures that reflect the combined action of several aspects of the environment governing a more aggregated response of the components [4]. FSI is representative of the latter. Both types of measures are necessary to present fully the combined effects of pollutants on a complex system, such as a forest exposed to the many variables present in the environment. Annual height and diameter growth of forests, which represent year-long responses to both air and soil chemistry, represent an annually integrative measure of the responses to these conditions, but FSI represents a longer-term measure, and one that is predictive with respect to the next generation of forests on that site.

BACKGROUND ON ACIDIC INPUTS AND FOREST EFFECTS

Studies of the effects of acidic deposition on forest growth have been underway for some years in Sweden and Norway and have been summarized [19–22]. The early work in Sweden by Jonsson and Sundberg [19] used tree-ring analysis methods, and the finding of possible effects was couched in considerable uncertainty. A later study was not able to support the original findings of effects from acidic deposition, but more recent research in Sweden, shows that certain very sensitive soil conditions, negative effects on tree growth can be demonstrated [23]. On naturally acid soils and on fertile, well-buffered soils no effects are expected and none are being found.

Experimental approaches for detecting effects of acidic deposition on tree growth have been undertaken in Norway [12,20,21]. These have led to the conclusion that over the period of a few years, the initial beneficial effects (on some soils) from the nitrogen and sulfur content in acidic deposition can be reversed over a period of time. In addition, the negative influence apparently due to the loss of soil cations (and possibly the toxicity of moderately elevated aluminum concentrations) combines to reduce the growth of trees [21]. The more general findings by Abrahamsen [12] suggest the effects from acidic input may be negative more frequently on soils of only moderately low nutrient status but potential magnesium or potassium deficiency. Where nitrogen and sulfur are the principal nutrient deficiencies, however, the response is likely to be positive in the short term, but negative in the long run. Abrahamsen gives no specific criteria as to how widespread each of these soil deficiency types may be in Norwegian forests.

Studies in Germany [24] have led to the conclusion that mobilization of aluminum (under situations of unusually high H^+ concentration) has produced negative effects on Norway spruce fine roots such that reduced growth and associated disease symptoms (extending to mortality) are being observed. Similar effects

on diameter growth in association with fluctuations in rainfall pH and a downtrend in stream pH have been reported by Johnson et al. for pitch pine in New Jersey [18]. Other studies reported by Johnson et al. (Chapter 7) show altered growth rates of red spruce in Vermont. Toxicity from free ionic aluminum (Al^{3+}) mobilized by acidic deposition, particularly during flushing episodes such as described by Johnson et al. [25], appears to be the most plausible explanation.

The results of several studies in Scandinavia, particularly those of Bjor and Teigen [22], suggest that estimates of the magnitude of cation removal from the surface layers of soil due to measured acid inputs may be possible. For the case of the shallow soils studied in Norway, a total stock of calcium + magnesium + potassium in the surface layers (in meq-m^{-2} to a 35-cm depth) can be summarized for both "before" and "after" treatment. The differences, representing experimentally induced time treatments of 0.4–280 y, indicate a loss of up to 50% of the Ca and a smaller portion of the Mg and K over the full period, even after allowing for the intervening release of weathering products. The total quantities leached during the experiment are larger than the initial nutrient stocks.

An analysis of the prospective effects on forest growth from acidic deposition must take into consideration and try to quantify the following four pathways by which effects can be expressed:

1. magnitude of growth reduction by exposure to oxidants;
2. direct foliar (carbon uptake) effects of acidity and other constituents in acid-altered precipitation;
3. effects on tree growth that may be attributable to a reduction in the stock of the nutrient cations in the soil or associated alterations of the cycling of nutrients such as N, P, K and S; and
4. extent to which episodic mobilization of toxic forms of aluminum in the soil solution can produce effects on tree roots and, therefore, on aboveground growth responses.

Indeed all four of these factors could operate simultaneously, and a potential exists for synergistic effects.

CASE STUDY FROM WISCONSIN

A data base within which to examine the utility of forest mensurational methods for analysis of pollutant-related tree-growth effects exists from the mid-1960s for quaking aspen in northern Wisconsin [17,26]. A portion of these data has been adapted specifically for obtaining aspen site index estimates solely on the basis of physiographic, soil and nutrient stock data for these sites (Table I). Simple regression models were developed from the site index and soil chemical data, with the results shown in Table II. The low (to negative) correlations reflect both the low nutrient demand of aspen and, in the case of phosphorus, an apparent interaction between water-holding characteristics and soil phosphorus (dry soils with slightly higher P, soils with a water table at depth but low P). Nitrogen levels showed no correlation with growth rates.

Table I. Mean and Range of Site Index and Independent Variables for 32 Quaking Aspen Stands [17]

Variable	*Mean*	*Range*
Site Index	76.5	65–88
Sand, B2 (%)	52.1	2.0–94.0
Silt, B2 (%)	30.0	2.0–80.0
Clay, B2 (%)	15.3	6.0–30.0
AWC (cm of Water)		
12-in. Depth	2.48	1.4–4.4
60-in. Depth	10.9	5.1–16.7
Water Table Depth (in.)	101.8	40–120+
Exposure	3.2	1–5
Ca (lb/ac to 12 in.)	1,044.6	303.3–3,027.6
Mg (lb/ac to 12 in.)	281.1	60.9–570.1
K (lb/ac to 12 in.)	157.4	99.8–257.0
P (lb/ac to 12 in.)	82.7	16.6–318.3
Ca (lb/ac to 60 in.)	5,946.4	1,505.5–15,967.8
Mg (lb/ac to 60 in.)	2,001.3	227.2–6,203.8
K (lb/ac to 60 in.)	854.9	419.5–1,666.9
P (lb/ac to 60 in.)	485.0	45.6–1,060.1

Table II. Correlations Between Site Index and Nutrient Levels for 30 Quaking Aspen Stands in Northern Wisconsin[a] [25]

	Correlation Coefficients			
Nutrient (lb/ac)	*12-in. Depth*	*24 in. Depth*	*36-in. Depth*	*60-in. Depth*
P	−0.474[b]	−0.454[b]	−0.514[b]	−0.557[b]
K	0.277[c]	0.420[c]	0.440[b]	0.469[b]
Ca	−0.071	0.109	0.240	0.311[c]
Mg	0.087	0.344[c]	0.392[c]	0.392[c]

[a] Only stands on sites with water tables deeper than 120 in. are included.
[b] Significant at 0.01 level.
[c] Significant at 0.05 level.

In addition, multiple regression models were developed and tested; the principal model was [17]:

$$\text{Aspen SI}_{(\text{age 50})} = 73.48 + 3.85\text{AWC} - 0.09\text{WTD} + 1.64\text{Exp} + 0.0012\text{Mg}$$

where AWC = available water capacity (cm of water), to 60 inches
WTD = water table depth (in.)
Mg = magnesium nutrient stock (lb/ac)
Exp = stand exposure expressed in a nominal scale

Table III. Initial Magnitude and Posttreatment Quantities of Three Cation Nutrient Stocks in a Norwegian Study and a Comparison with Stocks in Northern Wisconsin [17]

	Ca	*Mg*	*K*
Norwegian Study			
Initial			
(meq-m^{-2} to 35 cm)	125	20	28
Posttreatment			
pH 4 (9 years)			
meq-m^{-2} to 35 cm	98	14	25
% lost	22	30	11
pH 3 (90 years)			
meq-m^{-2}	14	2	24
% lost	89	90	14
Wisconsin Study			
Initial (lb/ac to 12 in.)	300–3,000 (1,050)	60–570 (280)	100–250 (155)
Posttreatment (meq-m^{-2} to 12 in.)	1,680–16,800 (5,880)	558–5,301 (2,604)	287–717 (445)

This equation, however, accounts for only 68% of the variation in site index. The variability of the data base for these models is illustrated by the means and range of major site properties shown in Table I. Ca and K showed small positive regression coefficients, but they correlate with Mg and only one of the nutrients is needed in the regression.

The Bjor and Teigen results [22] suggest the possibility, however, that at some future time it may be possible to estimate experimentally the long-term cation removals from poorly buffered soils in a region such as northern Wisconsin. With a sustained application of acidic materials (applied at pH 3 and 4), their data (Table III) suggest that over a period of 2–3 decades, perhaps 40–70% of the calcium and magnesium nutrient stocks could be leached from the surface rooting zone of their very low-nutrient soils. The corresponding stocks of these three elements in northern Wisconsin (to a depth of 12 in.) are summarized in the lower part of Table III. Even the poorest soils in northern Wisconsin show 10–20 times the Norwegian nutrient stocks, however, and average sites are about fivefold higher still. Since very small residual cation stocks tend to resist leaching and are retained as a continuing low percentage base saturation, the low-nutrient sites in Wisconsin could show similar cation losses for the same relatively strong acidic inputs, but the percentage reduction would be lower due to the higher initial stocks. For an illustrative computation, and given the pH 4.5 rainfall of northeastern Wisconsin [4], one could say that on the order of 10–30% of the Ca and Mg stock might be leached from the low-nutrient sites in a 25-y period, and 2–5% from the intermediate sites. The acid neutralizing capacity of the "high nutrient" sites appears to be sufficient to neutralize all acid inputs without appreciable percentage reductions in Ca and Mg stocks.

Table IV. Example Regression[a] Solutions for Effects of Mg Leaching on Aspen Site Index in Northern Wisconsin to 1990

	Mg Stock × Mg r Coeff.	*Calculated Aspen SI (ft)*	*ΔFSI 1965–1990 (ft)*
Case 1[b]			
1965 Mg Effect	220[c] × 0.0012	73.8	
Possible 1990 Mg Effect	220 × 0.75[d] × 0.0012	73.7	0.1
Case 2[e]			
1965 Mg Effect	2000[c] × 0.0012	75.9	
Possible 1990 Mg Effect	2000 × 0.97[f] × 0.0012	75.8	0.1

[a] Regression abscissa = 73 5 ft.
[b] 25% loss of Mg over 25 y on "low-nutrient" sites.
[c] Regression model was calibrated to total nutrient stocks (lb/ac) to 60 in., rather than the 12-in. value shown in Table III.
[d] Assumes, for illustration, a 25% leaching of the Mg stock over 25 y.
[e] 15% loss of Mg over 25 y on "intermediate" sites.
[f] Assumes, for illustration, a 3% leaching of the Mg stock over 25 y.

These calculations of possible cation losses, together with the prealteration regression model that includes a cation component, suggest a procedure by which one might estimate effects from this one aspect of pollutant loadings (cation stripping) on future forest growth rates. In effect, such computations represent a hypothesis to be tested against future field observations over several decades. An example computation is shown in Table IV, using Mg alone (the only cation whose influence on aspen site index in northern Wisconsin was significant). The regression model for trembling aspen is shown for the effect of Mg in the baseline year (1965), as well as for the year 1990 with a reduced stock of Mg. Given the modest amount of the variation in site index accounted for by the model, no significance can be attached to the estimate of 0.1 ft reduction at 50 y, but the methodology is illustrated.

At the low range of aspen site index, factors other than nutrient status appear to dominate growth, possibly because the multiple regression form without transformations tends to linearize the response over the entire observed range. With further analysis, the effects of Mg and Ca limitation on site index in the low nutrient range could be much larger. The effect of a shift of 0.1 ft in site index calculated for 1990 under either low or intermediate nutrient stocks can be summarized as follows:

- From aspen yield tables [27], a FSI of 80_{50} (i.e., 80 ft at 50 y) gives a mean annual growth of 70.6 ft³/ac/y.
- For aspen FSI 70_{50}, mean annual average growth is 62.15 ft³/ac/y.

Thus, for the above alteration in site index, 0.1 ft at 50 y by 1990, for "low" and "intermediate" sites, the change in total growth can now also be calculated. Assuming a linear interpolation in the difference in harvest at 50 y for SI

80 vs SI 70 (3531 vs 3103 ft^3, respectively), the change induced by a loss of 0.1 ft in height would be 5 ft^3.

Since other interactions also may come into play when a single factor is manipulated without transformation at the data limits of a multiple regression model, and these could influence the results, the effects of Ca and Mg depletion from low-nutrient sites could be larger than indicated here. Therefore, these results illustrate a methodology and suggest that all aspects be evaluated fully during the course of further studies. The small indicated effect illustrated here could be much larger on the lowest-nutrient sites even for aspen, and larger for other species or still other regions with nutrient stocks more similar to those in Norway.

DISCUSSION

The above computations have focused on only one of the four principal pollutant effect pathways cited earlier in the chapter, but they serve to illustrate a possible predictive mode within which forest growth effects may need to be considered. Oxidant effects already can be expressed as wood volume reductions by modeling the alteration of foliage condition, and the direct effects of gaseous pollutants are becoming well documented from studies in local impact areas.

Of more concern is that, to date, all estimation procedures have had to neglect the potential effects of aluminum toxicity. The most important experimental data presently available for tree species are those of McCormick and Steiner [28], from a study showing that one variety of hybrid poplar was sensitive to moderate aluminum concentrations. The other species tested, at least under the experimental approach used (i.e., in aqueous solutions, rather than a medium utilizing fungal relationships between roots and soil), showed little effect from aluminum over the range of concentrations likely to be observed even in acid soils.

An important aspect of this question is the current indication of Al^{3+} concentration likely to be expressed in the rooting zone of soils experiencing acidic deposition. No good measurement methodology is available for determining these concentrations during the rapidly changing conditions of an acid flushing event. However, computational procedures developed by Johnson et al. [25] are available which use the readily measured H^+ concentrations. This methodology shows that in headwater streams during flushing events, in which a portion of the inflowing water has been in brief contact with surface layers of the soil, aluminum concentrations approaching 0.25 $mg\text{-}L^{-1}$ are being observed. Given the large (but relatively uncertain) dilution for Al^{3+} from soil solution concentrations to Al^{3+} in the stream water, a significantly higher concentration around the fine roots of trees in the surface layers is likely. Although determining precisely the significance of brief exposures of roots of trees in the natural environments is a critical research need, these data suggest Al^{3+} concentrations in the surface soil layers will be in the range of a few parts per million for short periods, a level that would be significant for the hybrid poplar studied by McCormick and Steiner [28].

Finally, the question of using the more readily available diameter measure-

ments from tree ring analysis to reconstruct a stand response in terms of basal area, height growth, FSI or total forest productivity also must be addressed. Many of the tree-ring methodologies use a sufficiently large number of stems for analysis that a concept such as "the tree of average diameter" can be defined and used. By a methodology such as stem analysis (see Figure 1), it is possible to reproduce the height development of a tree of "average diameter" and develop an algorithm for the change in rate of height growth (and of site index) associated with the pollutant-induced changes in diameter growth.

Several other considerations, however, may limit the FSI approach. One relates to the widespread use of all-aged management in forests, and the great difficulty in obtaining freely growing stems for measurement under these conditions. A second consideration stems from the basic assumption that the shape of the height/age response over time is relatively uniform over various sites. Although this is usually the case, it does not hold for all soils and produces variance that cannot be incorporated in most models predicting growth rate. To reduce differences due to these limitations, standard site index measurement methods must be used and interpreted in conjunction with some knowledge of the forest age-class distributions and specific soil types in the regions involved.

CONCLUSIONS

The goals here have been primarily an examination of a methodology that may be needed if the effects on forest growth from acidic deposition are to be quantified and evaluated in detail. Effects on growth from cation stripping alone, or any other single effect pathway, may never be found to be a controlling factor, but methods will be needed that consider all potentially significant mechanisms.

The effects of acid precipitation on a watershed/lake system are diverse and intricately balanced, especially when a mature forest ecosystem holding a large nutrient stock is present. As outlined above, forest mensurational methods, particularly site index, appear to offer an "integrative" tool for expressing the effects on or changes in forest productivity over many decades due to changes in pollutant loads over such periods. Use of the site index as an integrator of acid deposition effects on growth (via nutrient stripping or aluminum toxicity) ultimately has the principal advantage of being readily converted to harvestable product or other economic terms for cost/benefit analysis.

REFERENCES

1. Miller, P.R., Ed. *Photochemical Oxidant Air Pollutant Effects on a Mixed Conifer Forest Ecosystem—A Progress Report,* EPA-600/3–77–104, U.S. Environmental Protection Agency, Corvallis, OR (1977).
2. Smith, W.H. *Air Pollution and Forests* (New York: Springer-Verlag New York, Inc., 1981).

3. Loucks, O.L. "Models Linking Land-Water Interactions Around Lake Wingra, Wisconsin," in *Land-Water Interactions*, A.D. Hasler and J. Olson, Eds. (New York: Springer-Verlag, 1975), pp. 53–63.
4. Loucks, O.L., R.W. Usher, D. Rapport, W. Swanson and R.W. Miller. "Assessment of Sensitivity Measures for Evaluating Resources at Risk from Atmospheric Pollutant Deposition," Final Report to the U.S. Environmental Protection Agency, ERL, Duluth, MN (1981).
5. Scheffer, T.C., and G.C. Hedgcock. "Injury to Northwestern Forest Trees by Sulfur Dioxide from Smelters," Tech. Bull. No. 1117, USDA Forest Service, Washington, DC (1955).
6. Linzon, S.N. "Economic Effects of Sulfur Dioxide on Forest Growth," *J. Air Poll. Control Assoc.* 21(2):81–86 (1971).
7. Stone, L.L., and J.M. Skelly. "The Growth of Two Forest Tree Species Adjacent to a Periodic Source of Air Pollution," *Phytopathology* 64:773–778 (1974).
8. Karnosky, D.F. "Changes in Southern Wisconsin White Pine Stands Related to Sulfur Dioxide on Forest Growth," *Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems*, P.R. Miller, Ed., General Technical Report PSW-43, USDA Forest Service, Berkeley, CA (1980), pp. 238–239.
9. Legge, A.H. "Primary Productivity, Sulfur Dioxide, and the Forest Ecosystem: An Overview of a Case Study," in *Proceedings of a Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems*, P.R. Miller, Ed. General Technical Report PSW-43, USDA Forest Service, Berkeley, CA (1980), pp. 51–62.
10. Skelly, J.M. "Photochemical Oxidant Impact on Mediterranean and Temperate Forest Ecosystems: Real and Potential Effects," in *Proceedings of Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems*, P.R. Miller, Ed., General Technical Report PSW-43, USDA Forest Service, Berkeley, CA (1980), pp. 38–50.
11. McLaughlin, S.B., R.K. McConathy and D. Duvick. "Effects of Chronic Air Pollution Stress on Allocation of Photosynthate by White Pine," in *Proceedings of Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems*, P.R. Miller, Ed., General Technical Report PSW-43, USDA Forest Service, Berkeley, CA (1980), pp. 244–245.
12. Abrahamsen, G. "Acid Precipitation, Plant Nutrients and Forest Growth," in *Ecological Impact of Acid Precipitation*, D. Drables and A. Tollan, Eds. (Oslo: SNSF Project, 1980), pp. 58–63.
13. Overrein, L.N., H.M. Seip and A. Tollan. "Acid Precipitation Effects on Forest and Fish; Final Report of the SNSF Project, 1972–1980," Oslo, Norway (1980).
14. Bruce, D., and F.X. Schumacher. *Forest Mensuration* (New York: McGraw-Hill, 1950).
15. Spurr, S.H. *Forestry Inventory* (New York: Roland Press Company, 1952), pp. 299–320.
16. Forbes, D., Ed. *Forestry Handbook.* (New York: Roland Press Company, 1955).
17. Fralish, J., and O. Loucks. "Site Quality Evaluation Models for Aspen (*Populus tremuloides* Michx.) in Wisconsin," *Can. J. Forest Res.* 5(4):523–528.
18. Johnson, A.H., T.G. Siccama, D. Wang, R.S. Turner and T.H. Barringer. "Recent Changes in Patterns of Tree Growth Rate in the New Jersey Pinelands: A Possible Effect of Acid Rain," *J. Environ. Qual.* 10(4):427–430 (1981).
19. Jonsson, B., and R. Sundberg. "Has the Acidification by Atmospheric Pollution Caused a Growth Reduction in Swedish Forests?" Report 20, Inst. For Skogsproduktion (1972).
20. Abrahamsen, G. "Impact of Atmospheric Sulfur Deposition on Forest Ecosystems,"

Atmospheric Sulfur Deposition, D.S. Shriner, C.R. Richmond and S.E. Lindberg, Eds. (Ann Arbor, MI: Ann Arbor Science Publishers, Inc., 1980), pp. 397–415.

21. Tveite, B. "Effects of Acid Precipitation on Soil and Forest. 9. Tree Growth in Field Experiments," in *Ecological Impact of Acid Precipitation*, D. Drabløs and A. Tollan, Eds. (Oslo: SNSF Project, 1980), pp. 206–207.
22. Bjor, K., and O. Teigen. "Effects of Acid Precipitation on Soil and Forest. 6. Lysimeter Experiment in Greenhouse," in *Ecological Impact of Acid Precipitation*, D. Drabløs and A. Tollan, Eds. (Oslo: SNSF Project, 1980), pp. 200–201.
23. Anderson, F. Personal Communication.
24. Ulrich, B., R. Mayer and P.K. Khanna. "Chemical Changes Due to Acid Precipitation in a Loess-Derived Soil in Central Europe," *Soil Sci.* 130:193–199 (1980).
25. Johnson, N.M., C.T. Driscoll, J.S. Eaton, G.E. Likens and W.H. McDowell. "Acid Rain, Dissolved Aluminum and Chemical Weathering at the Hubbard Brook Experimental Forest, New Hampshire," *Geochim. Cosmochim. Acta* 45:1421–1437 (1981).
26. Fralish, J.S. "Site Indices and Rates of Conversion in Northern Wisconsin Aspen," PhD Dissertation, University of Wisconsin, Madison, WI (1969).
27. Schlaegel, B.E. "Growth and Yield of Managed Stands," in *Aspen Symposium Proceedings*, General Technical Report NC-1, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN (1972), pp. 109–112.
28. McCormick, L.H., and K.C. Steiner. "Variation in Aluminum Tolerance Among Six Genera of Trees," *Forest Sci.* 24:565–568 (1978).